APPLICATION OF BARIUM TITANATE CAPACITORS TO FREQUENCY SHIFT KEYING CIRCUITS

H. M. DRYER

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IN
ENGINEERING ELECTRONICS

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by
H. M. DRYER
Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of

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from the
United States Naval Postgraduate School

PREFACE

This work on the application of titanate ceramics to a frequency shift keying circuit began as a laboratory term project at the U. S. Naval Postgraduate School in the early part of 1953. It was inspired by remarks of Professors E. G. Goddard and C. E. Menneken, of this school, concerning the possible applications of nonlinear dielectrics to amplifiers and to telemetering systems. In addition to samples used in the experimental work, these professors provided encouragement and advice.

Investigation of the effects of certain additives on the properties of barium titanate was carried out in the Transducer Engineering Laboratory of the Bendix Aviation Corporation, North Hollywood, California. Dr. Leon Camp, the head of the laboratory, furnished guidance in this field.

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CHAPTER I

INTRODUCTION

1. Summary

The dielectric constant of certain ceramics, notably the barium titanate family, is a function of the electric field across them. A capacitor employing such a dielectric was incorporated in the tuned circuit of an oscillator. The frequency of oscillation was varied by applying an appropriate steady bias to the non-linear capacitor. By pulsing the biased capacitor with a low frequency square wave, a signal suitable for use in frequency shift keyed radio teletype systems of communications was obtained.

2. Advantages of Frequency Shift Keying

In conventional radio teletype communications each character is represented by a five digit binary code group, plus start and stop pulses which are used to maintain synchronism between transmitter and receiver. At a transmission rate of sixty words per minute each code pulse is twenty-two milliseconds in duration. With on-off keying such a system is vulnerable to noise and to fading. It is possible for a sustained noise burst to occur during an off pulse and look to the receiving machine like a legitimate on pulse. While a human operator might be able to differentiate between the noise and the signal by differences in intensity and pitch, it has not yet proven practical to incorporate such discriminatory abilities in our communications equipment. Further, since the signal is being transmitted intermittently, automatic gain control and output noise limiting circuits can not be used in the radio receiver.

Producing a frequency shift keyed signal involves extra system complexity, but there are certain advantages which justify this. When different frequencies are used to indicate on and off conditions, it is no longer possible for a noise burst to look like an on pulse. Since some sort of signal is being transmitted at all times, it becomes possible to incorporate automatic gain control and output limiting circuits in the receiver. This gives great improvement under conditions of flat fading. Frequency shift keying may be regarded as a limiting case of frequency modulation. The intelligence carrying power is dispersed over a small number of discrete sidebands, whereas with on-off keying this power is concentrated principally in two narrow sidebands close to the carrier frequency. With a frequency shift on the order of 850 cycles

per second, which is the current standard practice, the increase in bandwidth, approximately a hundred cycles per second or about six and a half per cent for the two cases under consideration, may provide a further small improvement when faced with selective fading. An overall increase in the signal to noise ratio, as compared to on-off keying, on the order of twenty decibles may be obtained through the use of frequency shift keying. (14)*

3. Advantages of the Proposed Method.

Of course, a price must be paid for this increased transmission realiability. The least of this is the increased bandwidth. The greater part is the increased complexity of the transmitter. In order to produce the desired frequency shift, the inductance, capacitance, or both of the circuit which generates the frequency must be altered. It is manifestly impossible to do this by physically varying circuit components, hence recourse is had to electronic means. Usually this involves some variation of a reactance tube modulator. In one typical equipment this requires three additional vacuum tubes, two in a balanced reactance modulator and one in a reactance amplifier, with associated circuitry. The size, weight, power required, heat dissipation, and cost of the unit are thus increased. The gain in transmission reliability is somewhat decreased by the loss in equipment reliability.

By employing a very small, light weight, barium titanate capacitor in the tuned circuit of the oscillator, the capacity, and so the frequency, may still be varied electronically without adding extra tubes. No significant increase in weight, size, power requirements, heat dissipation, or cost--all important factors in military equipment--result thereby. The useful life of a piece of ceramic is certainly much

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* Numbers pertain to bibliography.

greater than that of one, much less several, vacuum tubes.

4. Disadvantages of Proposed Method.

At present, the major disadvantage of this method of producing a frequency shifted signal is the sensitivity of the titanate ceramic to changes in temperature. In certain ranges of temperatures the dielectric constant changes more rapidly with respect to temperature than with respect to the electric field imposed upon it. Memory effects, caused by thermal and electrical hysteresis in the ceramic, are minor annoyances. (One successful method of achieving temperature stability is described herein; undoubtedly others, some superior to this, will be evolved. The variations caused by memory can be lived with as indicated by the experimental results.)

CHAPTER II

PROPERTIES OF TITANATE CERAMICS

1. Terminology

In the following remarks on the properties of titanate ceramics, it will be necessary to employ some of the terminology of crystallography. Since crystallographers do not agree on a single standard vocabulary, it may be well to define the expressions to be used at the outset. The *unit cell* is the smallest parallelepiped from which a particular crystal may be constructed. The *crystal axes* are a system of coordinates parallel to the edges of a unit cell. The axes are labelled a, b, and c. The unit distances along the axes are proportional to the dimensions of the unit cell. In a *cubic* crystal the axes are mutually perpendicular, and the intercepts are equal. In a *tetragonal* crystal the axes are again mutually perpendicular, the intercepts along a and b are equal, but that on c is larger. In an *orthorhombic* crystal the axes are once more mutually perpendicular, but none of the intercepts are equal. In this case $c<a<b$. A *trigonal* crystal has four axes: c is an axis of symmetry; a_1, a_2, and a_3 are equal in length, lying 120° apart in a plane perpendicular to c.

The *Curie Point* is the temperature at which the crystal structure of the ceramic changes. This is variable with respect to the chemical composition and pressure. Barium titanate is characterized by three such points. Most authorities refer only to the change which occurs at about 120°C. as the Curie Point, and to the others as *transition points*. Accompanying these structural changes are changes in the properties of the material. Several of these properties are of interest.

Piezoelectricity is electric polarization produced by a mechanical strain, proportional to the strain and changing sign with it. Conversely, application of an electric field produces a mechanical strain proportional to the electric field. Some crystals are naturally piezoelectric and others may be treated in such a fashion that they become piezoelectric. This treatment is termed *polarization*. *Electrostriction*, a property of all dielectrics, is a distortion which is proportional to the square of the electric field. This effect is usually negligible, but in the case of certain ferroelectric substances it is of considerable magnitude. *Ferroelectricity* is spontaneous electric polarization of an otherwise unpolarized material over a definite temperature range.

Barium titanate is a ferroelectric material in which the electrostrictive effect is large. In addition, by the application of a polarizing field it may be made to be piezoelectric, with considerable remanent polarization. Another property possessed by this material is *pyroelectricity*, a change in polarization with temperature. While the direct effect is of greatest importance to those who fabricate the ceramic, the converse effect, a change in temperature with an applied field, does bother the user of this material.

The above definitions follow the usage of Cady (3) and Mason (17).

2. Behavior of Barium Titanate

Above the Curie point, barium titanate is cubic. At each corner of the unit cell is a barium atom. In the center of each face is an oxygen atom, while in the center of the cube is a titanium atom. The titanium makes a covalent bond with one of the oxygens at all times and may be displaced towards it. In this phase, the thermal energy of the crystal is sufficient to make any one of the six possible positions

for the titanium atom equally probable. The material is neither piezo- nor ferroelectric in this state. At the Curie Point, the dielectric constant is a maximum, falling off rapidly on either side. (Above the Curie Point this variation is approximately that predicted by the Curie-Weiss Law

$$K = Ko \not- C/ (t-to)$$

where Ko is the limiting value of the dielectric constant for temperatures much higher than the Curie Point, C is a constant, t is the temperature, and to is the Curie Point temperature.)

When the temperature is decreased below the Curie Point, the thermal energy is no longer sufficient to make all six of the possible positions for the titanium atom equally probable. Most of the titaniums in a region (or domain) tend to line up in a particular favored direction. The axis along which the titanium has been displaced becomes longer than the other two, the structure is now tetragonal, a dipole moment developes in the direction of the longer axis, and the material is ferroelectric in one direction. However in multidomain single crystals or in polycrystalline samples, these domains are oriented at random with respect to each other and the net polarization is zero. In this and subsequent phases, the barium titanate may be polarized to produce piezoelectric effects. After the initial sharp drop in dielectric constant near the Curie Point, the decrease continues slowly with temperature until a second transition point is reached.

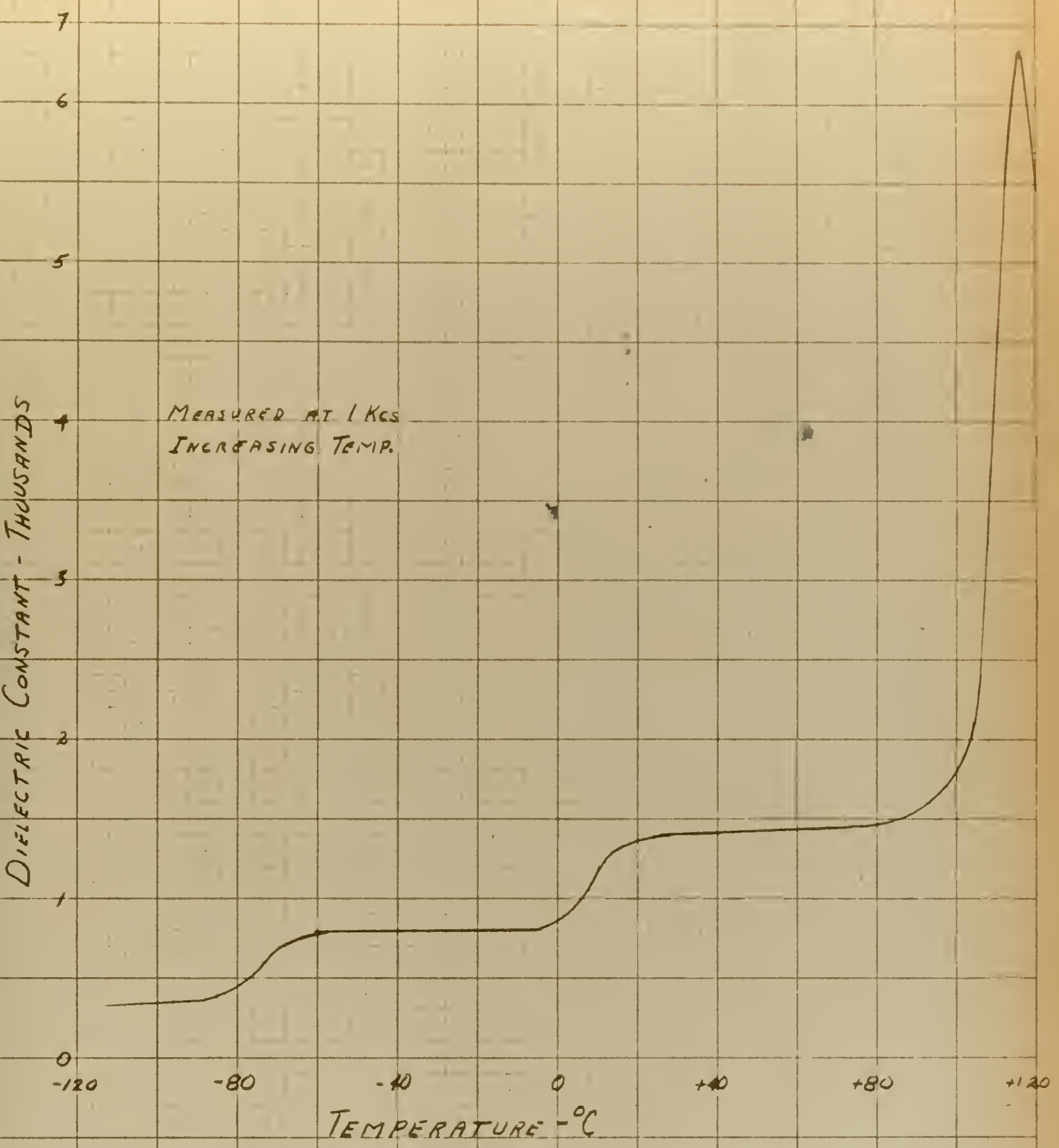
The second transition point comes at about 10°C., occurring higher for rising temperatures than for falling. In this stage the thermal energy has lessened to the point where the titanium may be displaced in two favored directions instead of just one, and apparently spends equal times in both positions. In this phase the crystal has become orthorhombic,

and exhibits ferroelectric properties along the two favored axes. A second sharp drop, of smaller magnitude than the first, in dielectric constant occurs here.

Following the sharp drop, a steady decrease with temperature again takes place and continues to about -80°C. at which temperature there is a third transition. In this phase, which apparently continues down to absolute zero, the structure is trigonal. The titanium can now spend equal times in any one of three positions, and the crystal displays ferroelectricity along three exes. At this third transition point the decrease in dielectric constant is less pronounced and not as sharply defined as at the two preceding ones. And finally the gradual decrease of dielectric constant with temperature resumes, reaching a minimum value of about ninety at absolute zero.

Figure 1 is a plot of the temperature variation of dielectric constant for polycrystalline barium titanate as determined by von Hippel, (21). The data were measured at one kilocycle per second for increasing temperature. It must be pointed out that at this time the production of titanate ceramics is less a science than an art. The properties and behavior of the finished ceramic is dependent upon the purity of the raw materials and the method of manufacture. (4) (8) (19). Properties vary not only from lot to lot of the ingredients, but also from batch to batch of the same lot. Theoretical considerations are of slight avail in these fields; only tedious experimentation is providing concrete answers. Still unsettled are such basic questions as the optimum firing cycle for vitrifying the ceramic.

Here too it must be noted that the properties of barium titanate test bodies vary with frequency and with applied field as well as with



Dielectric Constant of Barium Titanate vs Temperature

Figure 1

temperature, pressure, and composition. [illegible] are typical of a crystal structure, and so to completely described the conditions of measurement must be carefully and completely stated. One group of experimenters (13) who thoroughly investigated the variations in barium titanate dielectric properties found that even exposure to light with high ultra-violet content changed the dielectric constant of their samples. This may be an explanation of why the dielectric constant seems to be a function of time too.

As previously described, barium titanate is ferroelectric at ordinary room temperatures. Because the usual test body is a piece of polycrystalline material with the individual crystals and domains randomly oriented, the net polarization is zero. When a strong static electric field is applied to the specimen, the individual domains tend to align themselves with this field, producing a common component of polarization. Upon removal of the field, the sample remains polarized and it is now piezoelectric. The amount of residual polarization depends upon the composition of the sample, the magnitude of the polarizing field, the temperature at which polarization was carried out, and the length of time the polarizing field was maintained. (The polarization process is greatly similar to the magnetization of ferrous materials.) In the first two hours following polarization, there is a decrease in residual polarization which is on the order of twenty per cent and thereafter the residual polarization remains substantially constant. The remnant polarization may be destroyed in two ways however; by heating the sample to or near the Curie point, or by subjecting it to a field of polarity opposite to the polarizing field and of comparable magnitude.

Significance of Barium Titanate Behaviour.

In elementary electrostatics it is shown that when a linear homogeneous dielectric is exposed to the influence of an electric field, E, polarization, P, results from the tendency of orbital electrons and nuclear protons to align themselves with the field. The relationship is expressed as

$$P = \epsilon E \tag{1}$$

in which ϵ is the electric susceptibility. By definition, the electric displacement, D, is

$$D = E + 4\pi P \tag{2}$$

Substituting (1) into (2) yields

$$\begin{aligned} D &= E + 4\pi\epsilon E \\ D &= E(1 + 4\pi\epsilon) \end{aligned} \tag{3}$$

The factor $(1 + 4\pi\epsilon)$ is termed the permittivity or dielectric constant, designated by the symbol K and is independent of E.

However, as barium titanate is neither linear nor isotropic, and the quantities D, E, and P are vectors, it is necessary to alter the defining equations slightly. The first modification is to consider only components which are parallel to E. Next, P is considered to be the resultant of several polarizations. That polarization caused by electron migration is P_a. As before, this is proportional to the field, and no mechanical strain results therefrom. The polarization which results from the displacement of the titanium atoms as discussed in section 2 is designated P_d. Because the titanium atoms migrate with utter randomness

in the absence of a polarizing field, the net r_d is zero. When an external polarizing field exists, the titanium atoms tend to become displaced parallel to the field. In this case the crystal lattice is actually deformed and significant mechanical strains result, opposing the action which produced the strain. The resulting polarization is slightly decreased by the shielding effects of neighboring molecules, but it is somewhat enhanced if some oxygen atoms move towards the titanium atoms, as well as titanium atoms approaching favored oxygen atoms. The interplay of these actions causes r_d to become a transcendental function of E.

(Mason (17) presents a rigorous mathematical analysis of this mechanism, and empirically evaluates certain of the proportionality factors involved.)

Returning now to the defining equations, it is seen that

$$P = P_a + P_d$$

$$P = kE + f(E)xE$$

$$P = F(E)xE \qquad (1a)$$

and

$$D = E + 4\pi P$$

$$D = E + 4\pi F(E)xE$$

$$D = G(E)xE \qquad (2a)$$

where

$$G(F) = 1 + 4\pi\left[k + f(F)\right] \qquad (3a)$$

becomes the new expression for K, the dielectric constant.

Certain advantages accrue from being able to permanently polarize the ceramic. It has been experimentally determined that a polarized capacitor has a markedly decreased dissipation factor; decreases on the order of twenty to forty per cent of the unpolarized value are common. This is an important consideration when using a capacitor in an oscillator circuit. Further, in an unpolarized unit, the changes in dielectric constant are even functions of field; pulses of given magnitude will produce the same change in capacity regardless of polarity. For the polarized material these changes are odd functions, and are determined by both magnitude and polarity of the signal pulses which add to or subtract from the remnant polarization.

Although in general the dielectric constant is a transcendental function of the field, there does exist a small range of field intensities for which the variation in capacity is linear. To simplify the circuitry required to produce the values applied to the capacitor it is desirable to operate in this range. If the titanate could not be permanently polarized, this would require an extremely well regulated power supply for the biasing potential in addition to those power supplies otherwise required for equipment. Since remnant polarization can be produced, and as this remains constant, after the initial drop, for the life of the material, this critical power supply can be dispensed with.

Table I

EFFECTS OF POLARIZATION
UPON TITANATE CERAMICS

		Mix 1	Mix 2	Mix 3	Mix 4	
$PbTiO_3$		12.0	8.0	5.0	0.0	%
$CaTiO_3$		8.3	8.0	5.0	0.0	%
$BaTiO_3$		79.7	84.0	90.0	100.0	%
R	Before	100	76	64	56	ohms
	After	85	43	47	46	ohms
	Change	-15.0	-43.5	-26.6	-17.9	%
C	Before	868	1083	1435	2991	mmf
	After	895	1134	1494	3362	mmf
	Change	+3.10	+4.70	+ 3.97	+12.4	%
DF	Before	5.45	5.16	5.97	10.52	$x10^{-3}$
	After	4.78	3.06	4.56	9.71	$x10^{-3}$
	Change	-12.3	-40.5	-23.6	-7.70	%

Notes: $DF = R/X = \omega CR = 2\pi fCR$

Polarization carried out at 180°F. for four hours with a field of sixty kilovolts per inch.

Measurements made on ratio arm bridge at ten kilocycles per second and room temperature (85-90°F) no sooner than thirty-six hours after polarization.

Samples were rings, outer diameter 1.2", inner diameter 1.0", height .25", mechanically resonant at about fifty kilocycles per second.

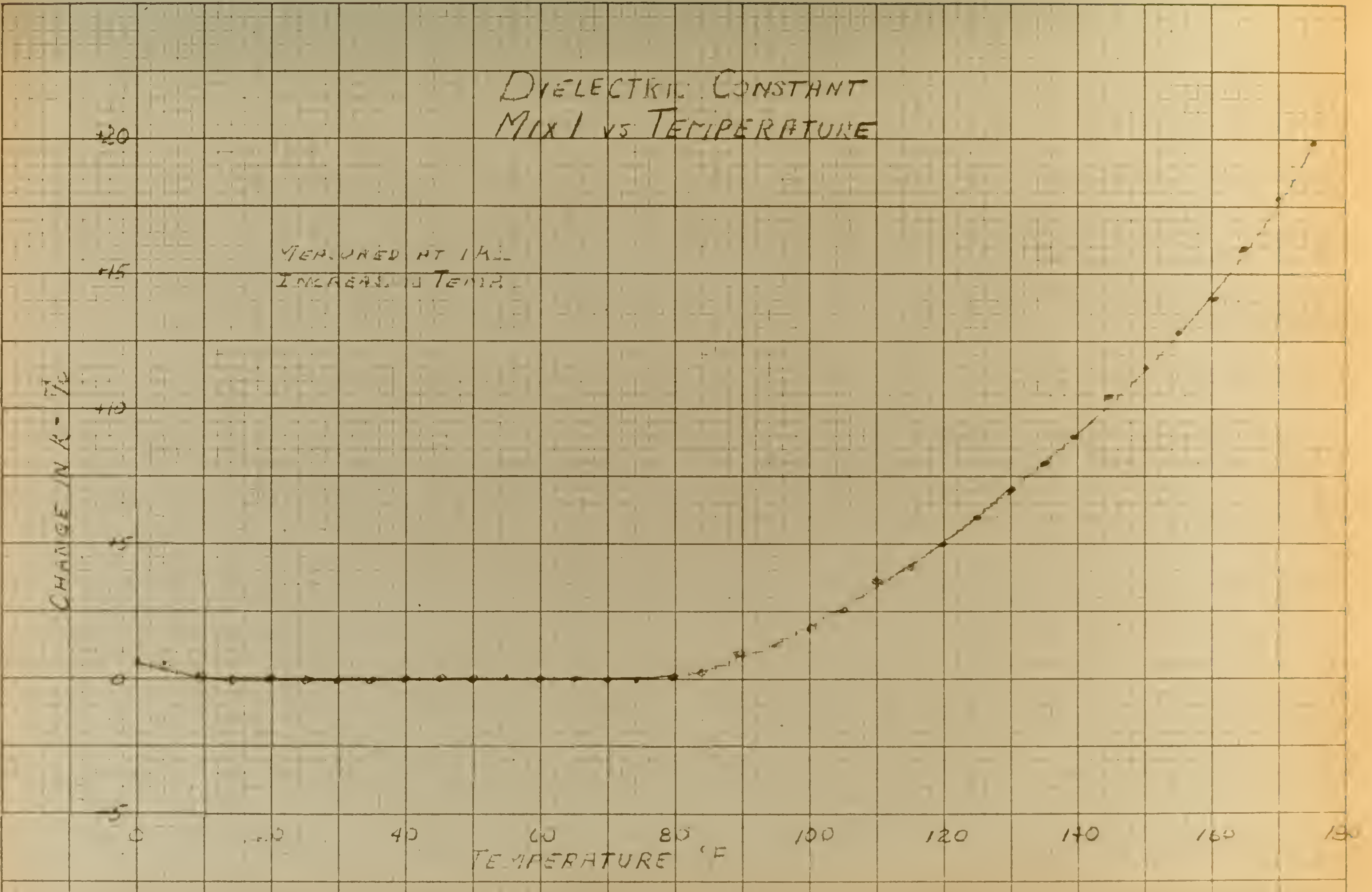
b. Effects of Additives

For applications such as those contemplated in this paper it is highly desirable that the properties of the ceramic used be invariant with respect to temperature. To attain this happy state, much work has been carried out to determine just what happens when other compounds, similar in crystal lattice structure and chemical nature to barium titanate, are added to the ceramic. Among the more thoroughly investigated materials are the stannates and titanates of lead, calcium, barium, and strontium. Tantalates and niobates have been experimented with more in the role of substitutes than of additives. (22) In general, additives shift the Curie and/or transition points and lower the dielectric constant. As the temperature difference between the Curie and transition points is increased, the dielectric constant tends to become more stable over an appreciable portion of the intervening temperature range.

Strontium salts lower the Curie point and broaden the peak in the dielectric constant versus temperature curve. Stannates produce much the same effect. (Tin and strontium effect the crystal lattice constants oppositely, (12) which points up the difficulty of trying to predict the behaviour of the ceramics from purely theoretical considerations at this time.) Lead compounds raise the Curie point and lower the second transition point. They also lower the piezoelectric effect. Calcium compounds lower the second transition point without effecting the Curie point. While yttrium oxide has much the same effect as a lead additive, and less is required to produce the same results, it is much too expensive at present for extensive commercial application.

In a recent symposium on barium titanate accelerometers (1[illegible]), it was reported that a ceramic composed of 1[illegible] lead titanate, [illegible].3% calcium titanate, and 79.7% barium titanate had optimum stability with respect to temperature. Experiment with this and other mixes indicate that a material composed of 8% each of lead and calcium titanates, 84% barium titanate is better suited for this application.

Figures 2,3,4,and 5 on the following pages illustrate experimental results in this area. The data were taken at a frequency of one kilocycle per second with increasing temperature. The test bodies were polarized rings of the mixtures listed in Table I. Because the dielectric constants involved are of greatly different magnitudes, the results are expressed as the percent change from the capacity of 70°C., a purely arbitrary choice of the normalizing factor.



DIELECTRIC CONSTANT
MIX I VS TEMPERATURE

MEASURED AT 1 KC
INCREASING TEMP.

FIGURE C

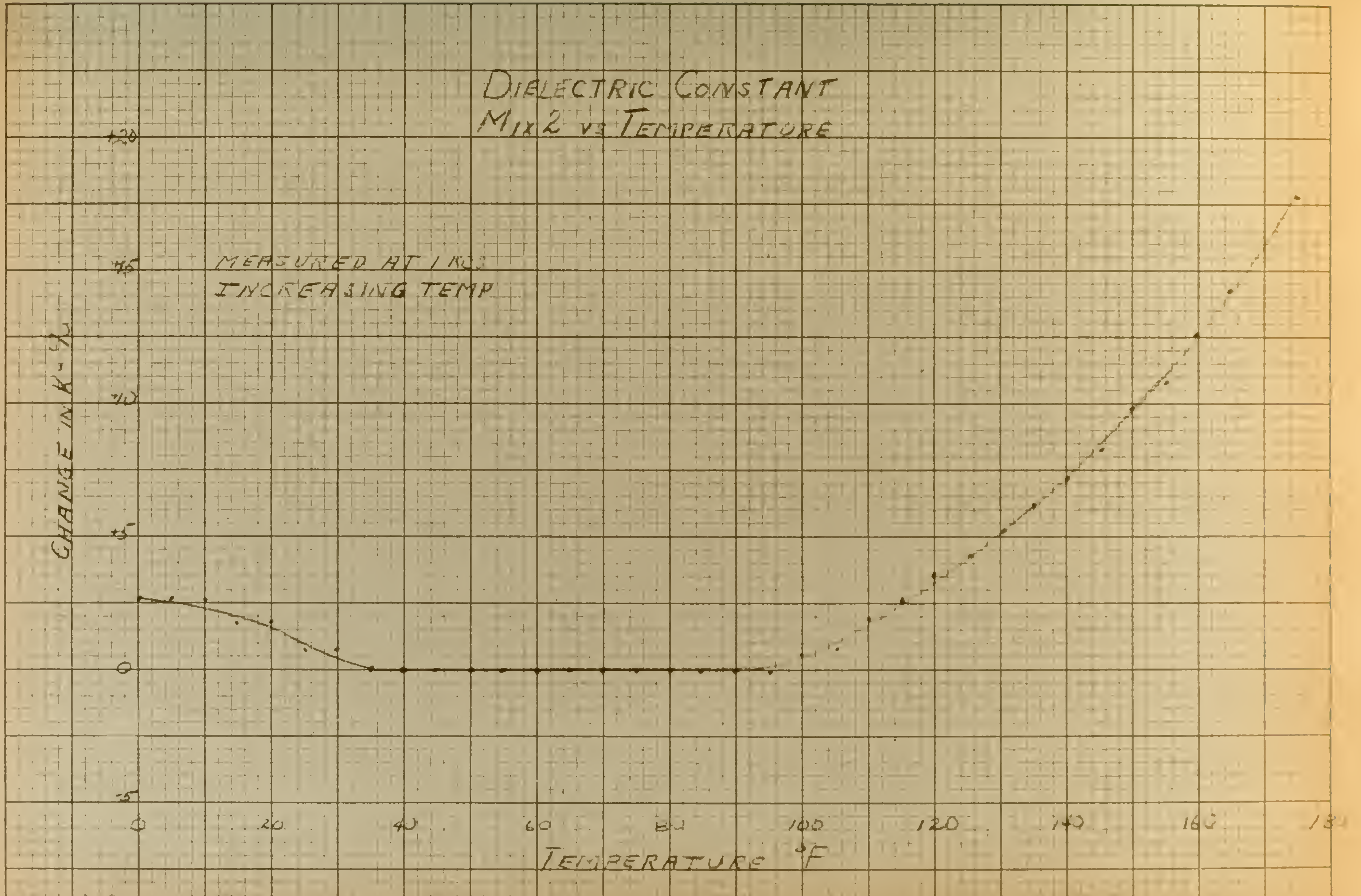

DIELECTRIC CONSTANT
MIX 2 VS TEMPERATURE
MEASURED AT 1 KC
INCREASING TEMP
CHANGE IN K - %
+20
+15
+10
+5
0
-5
0
20
40
60
80
100
120
140
160
180
TEMPERATURE °F

FIGURE 3

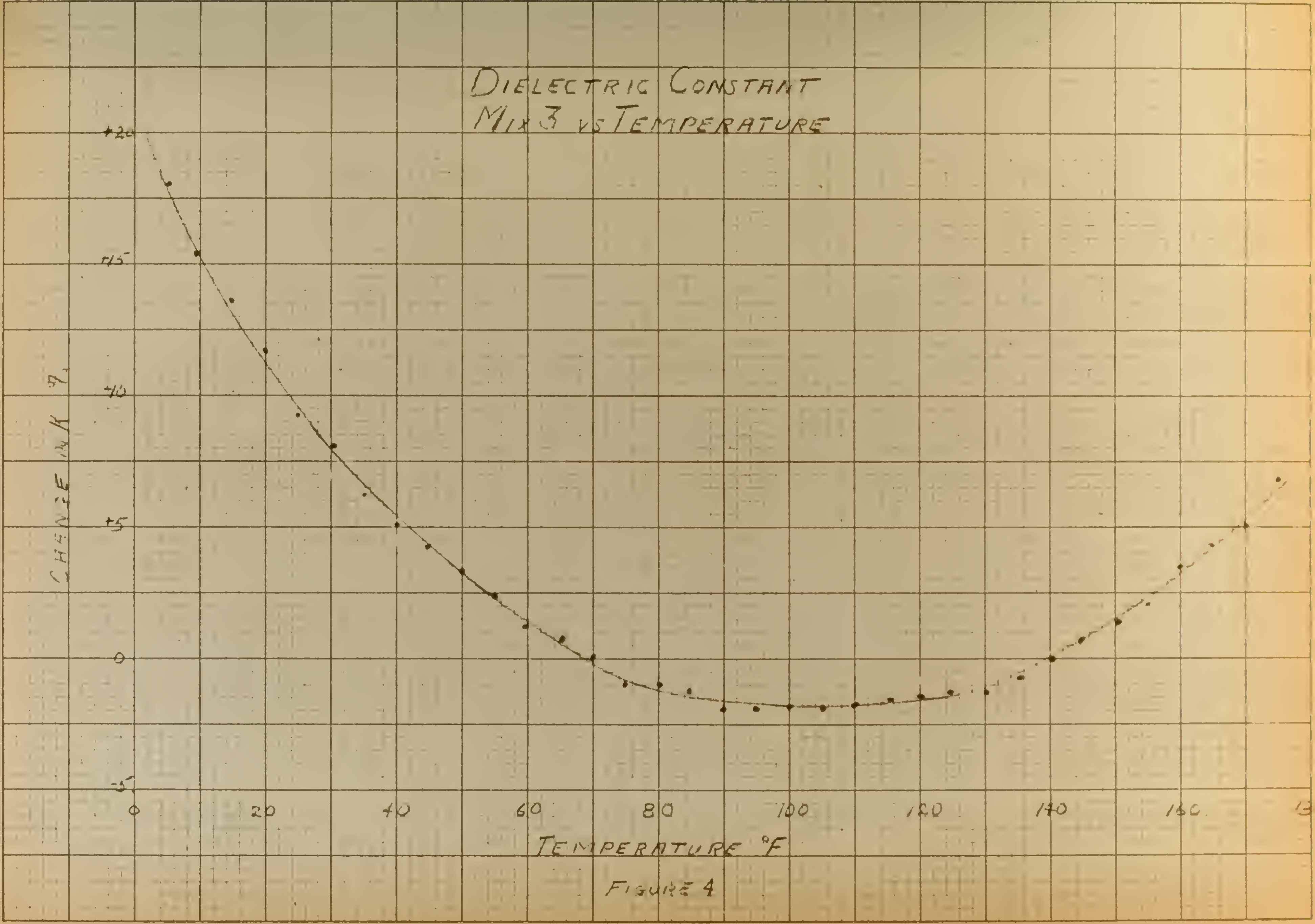

DIELECTRIC CONSTANT
MIX 3 VS TEMPERATURE
CHANGE IN K %
+20
+15
+10
+5
0
-5
0
20
40
60
80
100
120
140
160
TEMPERATURE °F

FIGURE 4

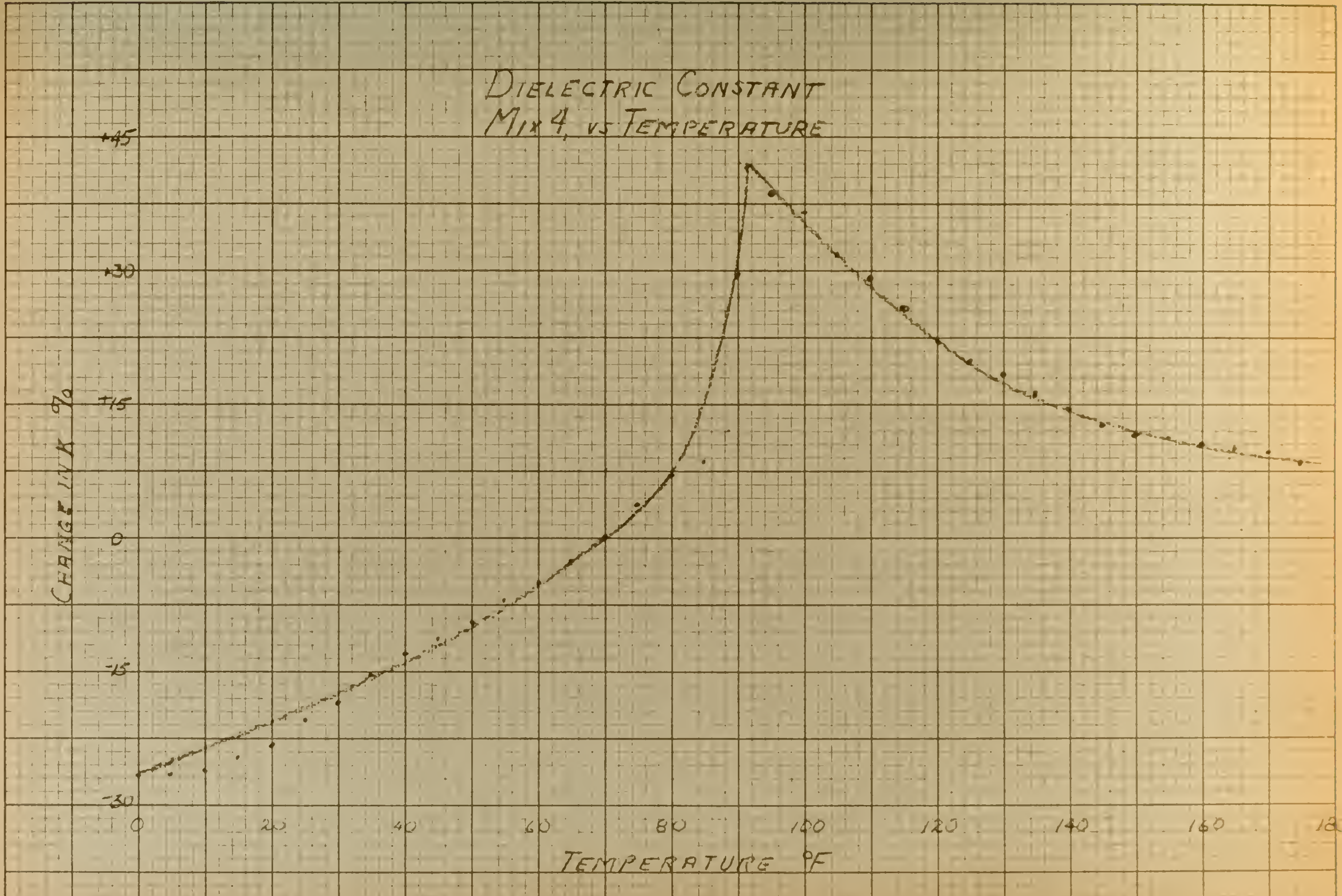

DIELECTRIC CONSTANT
MIX 4, vs TEMPERATURE
+45
+30
+15
0
-15
-30
CHANGE IN K %
0
20
40
60
80
100
120
140
160
TEMPERATURE °F

FIGURE 5

CHAPTER III

THE EXPERIMENTAL OSCILLATOR

1. Desired Characteristics

To verify the practicability of the proposed method of producing a frequency shift keyed signal, a variable frequency oscillator employing a titanate ceramic capacitor in the frequency determining portion of the circuit was required. It was deemed necessary that the oscillator possess an inherently high degree of frequency stability in order that unwanted frequency drifts (caused by tube capacitances shifting, for example) would not cloud the results of biasing the ceramic unit. Although normal radio teletype systems operate with a frequency shift of only 850 cycles per second, it was desired to be able to produce a shift on the order of a hundred kilocycles per second (to be able to later investigate the possibility of producing frequency modulation of a more general nature by this scheme). So that this deviation might not be too great a portion of the resonant frequency, the base frequency should be at least a megacycle per second.

The Clapp (Series Tuned Colpitts) Oscillator was considered to best fulfill the specifications broadly outlined above. (A detailed analysis of this circuit is given in Appendix I). Rather than employ separate oscillator and buffer amplifier stages, a pentode electron coupled circuit was resorted to for economy of tubes and components. Although normal practice is to operate the plate tank circuit at twice the frequency of the control grid circuit, it was decided to work both at the same frequency for better observation of possible distortion in the output wave form.

2. Titanate Samples

The most difficult part of the experimental work on which this paper is based was obtaining suitable samples of ceramic. The production of even small amounts of this material requires a large investment in dies, a press, and a well regulated kiln which were not available locally. However, three groups of samples were available. The first consisted of two capacitors, composition unknown, manufactured by the Gulton Manufacturing Corporation (of Metuchen, New Jersey). After much labor, these were discarded because a satisfactory degree of temperature stability could not be obtained with them. Measures taken to improve this stability included the use of thermal insulation, cooling with fans, and attempting to control the temperature of the samples with a crystal oven of the type employed in ultra high frequency radio equipments.

The second group of samples consisted of thin sheets of various ceramics, also prepared by the Gulton Manufacturing Corporation. On the basis of published data for these materials, the one which seemed most suitable was tried in the circuit. This too proved to be unsatisfactory although an appreciable improvement resulted. Apparently hysteresis losses (and perhaps the converse pyroelectric effect) were heating the samples. This caused the capacity and resistance of the material to shift, thereby varying the frequency. With the change in frequency, the current through the capacitor changed, altering the amount of heating that took place. The resultant change in frequency was sinusoidal in nature with an amplitude of about one kilocycle per second for the second sample (about one and a half kilocycles

per second for the first ones) and a period of thirty-five to [illegible] seconds. (Substituting an air dielectric variable for the ceramic capacitor removed this self modulation which indicated that the cause was some property of the titanate, not some defect of the circuit).

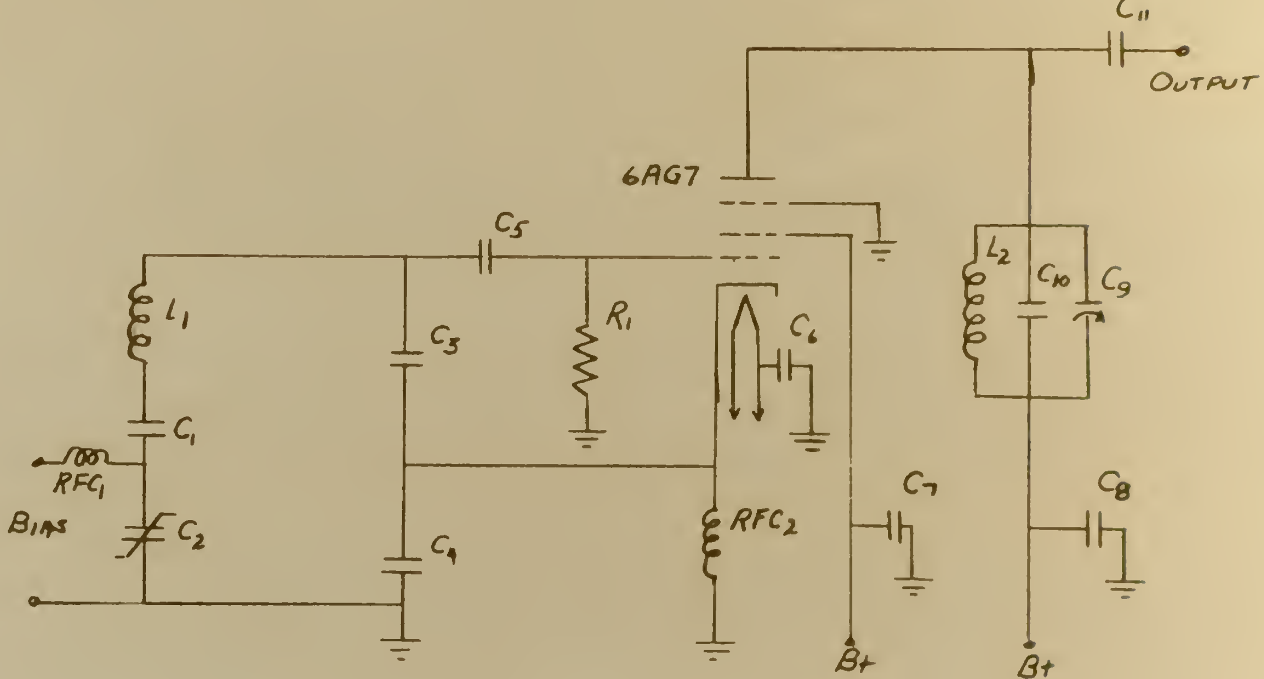
The third group of samples consisted of pieces of ceramic of mixture number two (8% each of lead and calcium titanates, 84% barium titanate) discussed previously. Several of these were sections of rings which had failed during attempted polarization. These proved to be too lossy to support oscillations in this circuit. A complete ring, which had not been polarized, proved satisfactory. This particular unit had a room temperature, unbiased capacitance of 1010 micromicrofarads, measured at one kilocycle per second.

3. Circuit and Construction Information

The circuit of the experimental oscillator (shown in Figure 6) is quite conventional(2) so only significant differences need be commonted on. The effective tuning capacitance, C_t, is C_1, a silvered mica, and C_2, the nonlinear titanate unit, in series. The magnitude of C_2 is much too large to use as is, so this reduces it to a usable value of

$$C_t = \frac{C_1 \quad C_2}{C_1 + C_2}$$

The change in C_t for a given change in C_2 is also reduced as is



L_1, L_2	50 μh
R_1	47 KΩ, ½ W
RFC_1, RFC_2	2.5 mh, 50 ma
C_1	500 μμf, silver mica
C_2	1010 μμf, Titanate

C_3 C_4	.005 μf, silver mica
C_5 C_{11}	100 μμf, mica
C_6, C_7, C_8	1000 μμf, mica
C_9	100 μμf, variable
C_{10}	470 μμf, mica

CIRCUIT DIAGRAM

FIGURE 6

seen by taking the differential of each side of the above equation,

$$dC_t = \frac{C_1^2}{(C_1 + C_2)^2} dC_2$$

This turns out to be an advantage as it is possible to produce a much greater change in C_2 by applying a bias to it than is produced by temperature variations. This reduction in the change of capacity therefore assists in attaining temperature stability at the price of requiring larger pulses to give the desired change. The presence of C_1 also serves to block the bias potential applied to the ceramic unit from the rest of the tuned circuit. Neither L_1 nor L_2 are shielded, but they are mounted with their axes at right angles to minimize mutual coupling between them. L_1 has an unloaded Q of 195 and L_2 has an unloaded Q of 95 (for broader response) at one megacycle per second. The choke coil, RFC_2, is provided to isolate the bias power supply from the radio frequency currents of the tuned circuit. C_3 and C_4, nominally equal in the Clapp Circuit, are here matched to within 0.4%.

4. Tests Conducted

Well regulated (Hewlett Packard 710A) laboratory power supplies were used during all tests to minimize frequency variations caused by voltage changes. A resistive voltage divider was used to provide screen grid and plate voltages from a common supply to increase frequency stability. The plate potential was set at 2 0 volts, and the screen grid potential adjusted for a screen grid current of five millamperes. The resultant plate current was

twenty-one milliamperes. (This seemed to yield maximum stability.) These operating conditions are well within the prescribed range for the tube used (a 6AG7).

Frequency determinations were made with two instruments, a Navy model LM-1 heterodyne frequency meter and the General Radio 834B Electronic Audio Frequency Meter. The 834 is a vacuum tube cycle counter. The LM contains two oscillators, a crystal controlled secondary frequency standard and a well calibrated beat frequency oscillator. The accuracy of both the crystal oscillator and the calibration is checked regularly against the transmissions of WWV. The stability of the LM was first investigated in the following manner. With the crystal oscillator energized, and the audio output of the LM fed to the input terminals of the 834B, the beat frequency oscillator was tuned to a frequency five hundred cycles per second higher than a check point (1142.86 kcs.). The changes in frequency were observed for a period of one hour. Random deviations of as much as twenty-five cycles per second, plus or minus, were noted. On the assumption that the crystal oscillator is stable to within ten cycles per second per megacycle per second, most of these deviations may be credited to either the beat frequency oscillator or the 834B. This yields an indication of the accuracy to be expected from the combination of these two instruments.

Next the crystal oscillator was turned off, and the output from the experimental oscillator coupled to the input terminals of the LM. The 834 was replaced temporarily with headphones, and the LM tuned for a zero beat note. With the 834B reconnected

to the LM, the tuning dial was advanced until a five hundred cycle per second beat note resulted, and the frequency variations again observed for a period of one hour. This type of run was made with biasing potentials of 0, 100, 200, and 300 volts applied to the ceramic unit. Maximum deviations for these runs did not exceed plus or minus fifty cycles per second and were of a random nature. The operating frequencies for these runs were 1140.95, 1140.70, 1140.15, and 1139.55 kilocycles per second respectively.

Next investigated was the frequency versus bias characteristics. (For this and subsequent tests head phones were used as null indicators and the 834B dispensed with.) The bias applied to the titanate capacitor was increased in ten volt steps, and the frequency measured. Upon reaching a value of 300 volts, the bias was decreased in ten volt steps and the corresponding frequencies again determined. Next the bias was cycled up and down in twenty-five volt steps to see how serious hysteresis effects would be. Results are plotted in Figure 7.

To simulate the proposed conditions of use, the bias on the nonlinear capacitor was varied between several different levels as rapidly as the frequency corresponding to each value of bias could be determined. Results are indicated in Table II. This test approximated a low frequency square wave signal, but admittedly did not approach the twenty-two cycle per second signal from a teletype. However, Apstein and Weider, (1) Donley, (9) and Dranetz et al.,(11) are among those who report having produced more general frequency modulation with a complex audio frequency signal by comparable methods,

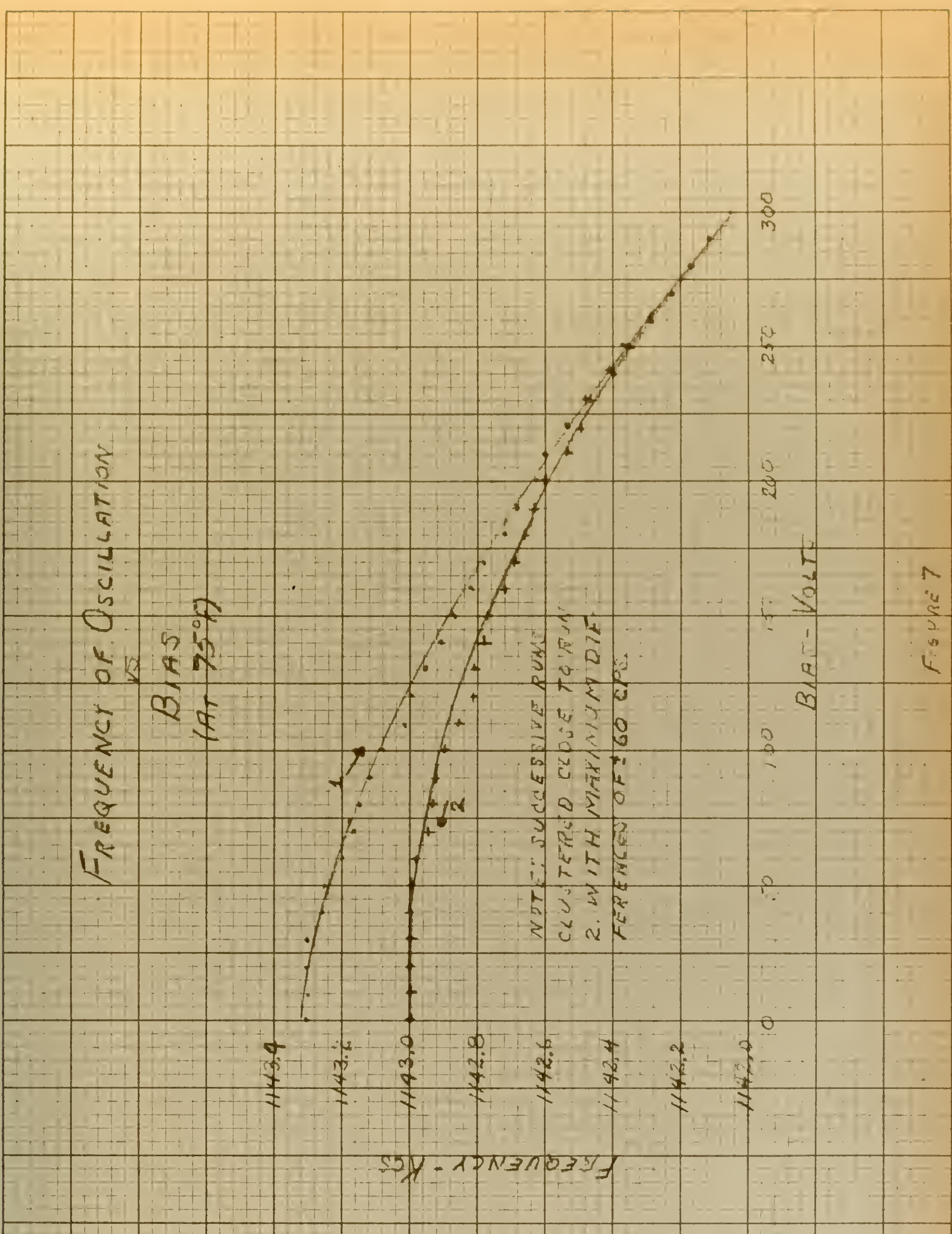

FREQUENCY OF OSCILLATION
vs
BIAS
(AT 75°F)
FREQUENCY - KCS
1143.4
1143.2
1143.0
1142.8
1142.6
1142.4
1142.2
1142.0
0
50
100
150
200
250
300
BIAS - VOLTS
1
2
NOTE: SUCCESSIVE RUNS
CLUSTERED CLOSE TO RUN
2. WITH MAXIMUM DIF-
FERENCE OF ±60 CPS.

FIGURE 7

without appreciable distortion. Bothersome time lag effects are not anticipated here.

It was desired to determine the harmonic content of the output wave. The frequency of the oscillator is outside the range of the harmonic wave analyzers available in the laboratory. If the signal were translated downward by suitable heterodynings and any appreciable distortion noted, the source of the distortion would not be uniquely determined; the culprit could be the beat frequency oscillator, the mixer, or the experimental oscillator. Nor could the relative magnitudes of the harmonics, if found, be determined accurately in this fashion. Therefore the output was examined visually with a Tektronix 511AD Oscilloscope. The bias on the nonlinear capacitor was varied, again in ten volt steps, from zero to three hundred volts. For each value of bias the picture on the oscilloscope was adjusted to show four cycles completely filling the ruled grid. No distortion could be seen. No improvement could be noted when an air dielectric variable capacitor was substituted for the titanate unit.

5. Conclusions.

The experimental data show that it is feasible to produce a frequency shifted signal by applying signal pulses to a suitable nonlinear capacitor. Several methods have been tried to insure temperature stability. The most promising of those seems to be the development of high Curie Point ceramics. It may be advisable to employ tantalates and niobates, instead of the more thoroughly investigated titanates, as they have Curie Points in the range of 200°C. to 350°C. (392°F. to 662°F.), transition points near 0°C. (32°F.), and are

TABLE II

RESPONSE TO SIGNAL PULSES

PULSE MAGNITUDE	BIAS VOLTAGE MAXIMUM/MINIMUM	MEAN FREQUENCY KCS	MAXIMUM DEVIATION CPS PLUS	MAXIMUM DEVIATION CPS MINUS
100 volts	300	1142.68	20	60
	200	1143.06	20	10
200 volts	300	1143.04	10	30
	100	1143.52	80	20
300 volts	300	1142.78	20	20
	0	1143.25	10	30

otherwise very similar to the titanates(22). A road of attack not tested is the use of positive temperature coefficient compensating capacitors. This approach was not evaluated because suitable units could not be obtained locally at this time.

At present a very large pulse is required to produce the required frequency shift. The nonlinear capacitor employed was 0.10 inch thick. As the proportional change in capacity is determined by the field strength produced by the pulse, the use of thinner units will enable the production of a given shift with a smaller pulse. (Gulton Manufacturing Corporation has perfected a technique whereby sheets of only several mils thickness can be produced. (11)) The required change in capacity can also be reduced by several means. Among these are frequency doubling in the plate circuit of the oscillator, and operating the oscillator at a higher base frequency since the proportional change in capacity required is twice the magnitude of the proportional change in frequency.

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APPENDIX I

ANALYSIS OF CLAPP OSCILLATOR CIRCUIT

The radio frequency portion of the basic Clapp Oscillator circuit is shown below. The losses of both L and C are assumed

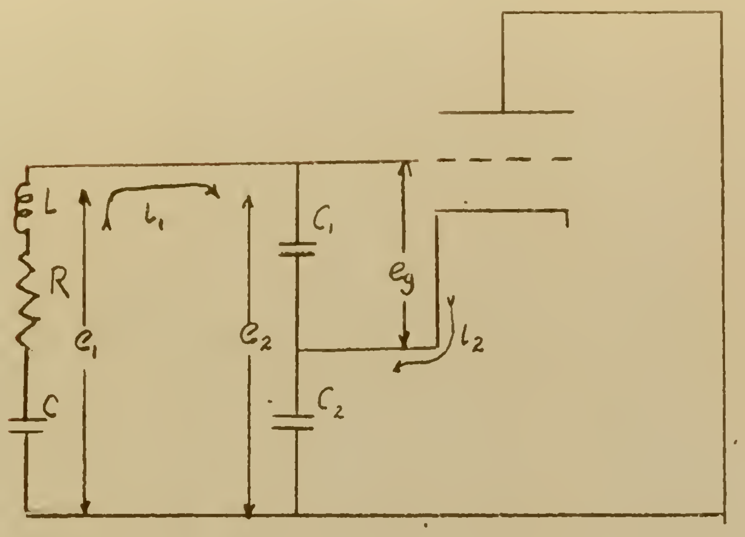

Figure 8. Basic Clapp Oscillator Circuit

to be lumped in R. For stable oscillations to exist, the energy dissipated in R must be supplied by feed-back, in this circuit across C_1 and C_2. Proceeding on the loop basis, it is seen that

$$e_1 = i_1 (R + j (X_L - X_c)) \qquad (1)$$

$$e_2 = i_1 (jX_1 + jX_2) + i_2 jX_2 \; . \qquad (2)$$

But

$$i_2 = g_m e_g = g_m i_1 jX_1 \qquad (3)$$

so that

$$e_2 = i_1 j(X_1 + X_2) - g_m i_1 X_1 X_2 \; . \qquad (4)$$

If e_1 equals e_2, then

$$i_1 \left(R + j(X_L - X_c)\right) = i_1 j(X_1 + X_2) - g_m i_1 X_2 X_3 \quad . \qquad (5)$$

When the fed-back energy equals that lost in R, stable oscillations exist, and e_1 does equal e_2. Dividing out the common factor, i_1, in all terms of (5), and equating the real and imaginary portions of each side, it is seen that

$$R = -g_m X_2 X_3. \qquad (6)$$

is a condition that must be satisfied for stability, and that the frequency of oscillations may be calculated from

$$X_L - X_c = X_1 + X_2 \qquad (7)$$

$$wL - \frac{1}{wC} = \frac{1}{wC_1} + \frac{1}{wC_2} \qquad (8)$$

$$wL = \frac{1}{wC} + \frac{1}{wC_1} + \frac{1}{wC_2} \qquad (9)$$

$$w^2 LC = 1 + \frac{C}{C_1} + \frac{C}{C_2} \qquad (10)$$

$$f = \frac{1}{2\pi\sqrt{LC}} \sqrt{1 + \frac{C}{C_1} + \frac{C}{C_2}} \qquad (11)$$

When C_1 equals C_2 then (11) reduces to

$$f = \frac{1}{2\pi\sqrt{LC}} \sqrt{1 + \frac{2C}{C_1}} \qquad (12)$$

When C_1 and C_2 are very much larger, say ten times or more, than C, small changes in C will not appreciably change the value of the last factor in equation (12) which may then be further simplified to

$$f = K \frac{1}{\sqrt{C}} \qquad (13)$$

Taking the differentials of (13) yields

$$df = -\frac{1}{2}K \frac{dC}{\sqrt{C^3}} \qquad (14)$$

Finally, dividing (14) by (13) gives an expression for the fractional change of frequency in terms of the fractional change of tuning capacity

$$\frac{df}{f} = \frac{-dC}{2C} \qquad (15)$$

It must be remembered that stray and tube capacities form part of C_1 and C_2. Since the physical capacitors employed are much greater than these extraneous additions, variations in the unwanted capacities will not greatly affect the circuit. In addition, the tuning capacitance, C, employed in this circuit is always considerably greater than that which would be employed in the conventional Colpitts or the Hartley circuits. Thus a given magnitude of change in C is a very much smaller portion of it, varying the frequency less.

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